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This report summarizes the technology developed by Optical Concepts during BMDO SBIR contract DASG60-94-0022. This material presented here is a condensed version of what is described in greated detail in the 8 quartely reports submitted during this program. In this program, Optical Concepts has developed a technology for fabricating wave-length-division multiplexed (WDM) arrays of long-wavelength vertical cavity surface-emitting lasers (VCSELs) operating norminally at 1550 nm. Prior to this program, 1550 nm VCSELs operating continous-wave (CW) at room temperture had not been demostrated. Optical Concepts has developed CW 1550 nm VCSELs during this program by integrating them with a 980 nm VCSEL optical pump. This optically pumped structure eliminates the need for dopants in the optical cavity, and reduces device heating, leading to CW operation with extremely low threshold gains. The low threshold gain allows fabrication of WDM arrays with a wide wavelength span.

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Final Report for DASG60-94-0022

Abstract

This report summarizes the technology developed by Optical Concepts during BMDO SBIR contract DASG60-94-0022. The material presented here is a condensed version of what is described in greater detail in the 8 quarterly reports submitted during this program. In this program, Optical Concepts has developed a technology for fabricating wavelength-division-multiplexed (WDM) arrays of long-wavelength vertical cavity surface-emitting lasers (VCSELs) operating nominally at 1550 nm. Prior to this program, 1550 nm VCSELs operating continuous-wave (CW) at room temperature had not been demonstrated. Optical Concepts has developed CW 1550 nm VCSELs during this program by integrating them with a 980 nm VCSEL optical pump. This optically pumped structure eliminates the need for dopants in the optical cavity, and reduces device heating, leading to CW operation with extremely low threshold gains. The low threshold gain allows fabrication of WDM arrays with a wide wavelength span.

I. Long-Wavelength VCSEL background

Since March of 1994, Optical Concepts, Inc. (OCI) has been working on BMDO contract DASG60-94-0022. This program has supported developing wavelength-stepped long-wavelength vertical cavity surface-emitting laser (VCSEL) arrays for use in wavelength-division multiplexed (WDM) communication systems. This program was motivated by the high cost of 1.55 μm single-mode sources such as Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) lasers. These devices cost thousands of dollars per device, and promise to cost much more when fabricated into wavelength-stepped arrays [1,2] for WDM.

VCSELs represent a potentially inexpensive solution to these problems. Single-mode devices can be fabricated and tested on a wafer scale, and more easily coupled to single-mode fiber than in-plane lasers. WDM arrays can be realized by simple wet chemical etching prior to deposition of a top mirror.

Unfortunately, 1550 nm VCSELs have been much more difficult to fabricate than 980/850 nm VCSELs. The primary reason is the absence of epitaxial mirrors with good index contrast and high reflectivity in the InP/InGaAsP long-wavelength material system. This problem is compounded by increased temperature sensitivity in the InP/InGaAsP system relative to GaAs/AlAs, and increased dopant-induced optical losses as well

The most successful 1550 nm results published to date in the open literature have been achieved in structures using at least one "wafer-fused" mirror, consisting of alternating layers of high index contrast GaAs/AlAs. Wafer fusion is a process whereby semiconductors of different lattice constant, such as GaAs and InP, can be atomically joined simply by applying mechanical pressure and heat. This process leads to optically and electrically clean interfaces. Wafer fused 1550 nm VCSELs have been pioneered by the University of California at Santa Barbara (UCSB) [3]. A structure employing two wafer fused mirrors and an InGaAsP active region for 1.55 μm operation is pictured in Fig. 1.1. This structure has recently achieved room temperature cw operation, but still suffers from a number of fundamental difficulties.

Although the wafer-fused structure of Fig. 1.1 solves the mirror reflectivity problem, it does not solve the problem of dopant-induced optical losses and temperature sensitivity. These problems arise from the way charge carriers are injected into the quantum-well active region. If one applies metal contacts to the semiconductor--so-called "electrical pumping"--resistive heating becomes a problem. In addition, electrical pumping necessitates dopants in the semiconductor cavity, which increase optical loss. These factors make the design window of the structure in Fig. 1.1 narrow, particularly when the device wavelength is detuned from the gain peak in a wide wavelength span WDM array.

Our solution to these problems is to *optically* pump the material. That is, one can inject light of a wavelength shorter than the desired 1550 nm emission. This light gets absorbed in the long-wavelength cavity and generates electrons and holes. These charge carriers in turn diffuse into the quantum wells and re-emit at the longer wavelength. This scheme requires no electrical contacts, so resistive heating is not a problem. In addition, since carriers are injected by light, the long-wavelength cavity can also now be free of dopants, which are the primary contributor to loss in that cavity.

II. The Optically Pumped Approach

We employ a 980 nm VCSEL array to optically pump a 1550 nm VCSEL array, using the configuration of Fig. 2.1. Previous optical pumping experiments on VCSELs have used an expensive high-power solid-state or dye laser as the source, making them impractical for commercial applications. Our optically pumped configuration, however, retains all the advantages of the VCSEL geometry, such as wafer-scale fabrication and testing. Modulation of the long-wavelength radiation is accomplished by modulating the 980 nm pump. If the long-wavelength cavity is correctly designed, around 30% of the 980 nm emission can be converted to 1550 nm emission. For example, a state-of-the-art 10

μm 980 nm VCSEL can deliver nearly 10 mW of power, so a long-wavelength cavity of comparable size be expected to yield 3 mW out. One of the reasons this scheme works so well is that the mirrors of the 1550 nm VCSEL are transparent to the 980 nm radiation. This allows the pump beam to be coupled efficiently into the long-wavelength VCSEL.

All of these advantages make the optically pumped approach particularly suitable to WDM arrays. The low required threshold gain allows the device to operate many tens of nm away from the gain peak, which is of utmost importance in, for example, a 16 channel system with 2 nm channel separation spanning 30 nm. Application of this "980 nm VCSEL pumping 1550 nm VCSEL" approach to fabricating 1550 nm WDM VCSEL arrays is the primary accomplishment of this program.

Before discussing experimental results in the following sections, we present a simplified theoretical projection of 980 nm to 1550 nm power conversion. We start with the basic equation governing conversion of 980 nm power P(.98) to 1550 nm power P(1.55) in our optically pumped approach :

$$P(1.55)=(P(.98)-P_{th})\ \eta_i\ \eta_{conv}\ (T/(T+A))$$

where

η_i= fraction of injected photons ending up as carriers in the wells

η_{conv}= energy loss from 0.98 μm to 1.55 μm=0.63

T= fractional transmission of top (output) mirror at 1550 nm

A=fraction of light lost to absorption/scattering/diffraction per roundtrip

P_{th} = pump power required to reach threshold

In this equation, the parameter η_i is determined by the thickness and absorption coefficient of the absorber surrounding the active quantum wells, and is usually around 0.85. The internal losses A are whatever residual losses remain after dopants have been removed. We assume this number is 0.1, based on work in 980 nm VCSELs. The threshold power is a function of whatever active medium we choose, the output transmission T, and the internal losses A. We choose an 18 μm device diameter, for comparison with data, an output

transmission T of 0.3, and strained quantum wells with gain characteristics detailed in [4]. From this information, we estimate that threshold power is 0.6 mW.

We now know all the parameters in the above equation, and are in a position to plot output power. This equation is plotted in Fig. 2.2 for our design. Figure 2.2 shows that over 2 mW of output power can be achieved with a 980 nm pump power of 6 mW. The best 10 μm 980 nm VCSELs today deliver nearly 10 mW, so Fig. 2.2 suggests that over 2 mW is possible with today's technology. We choose a pump diameter of 10 μm, because we would like the 1550 nm VCSEL to operate in the fundamental transverse mode. If the pump beam is pumping only the central portion of the 1550 nm VCSEL, fundamental mode operation should be obtained.

The power-out vs. power-in diagram of Fig. 2.2 is shown as linear over a large power range. Typical electrically pumped VCSEL curves show a rollover at large drive currents due to heating. We do not show such a rollover in Fig. 2.2 because heating during optical pumping is far less than that during electrical pumping. For a typical thermal impedance of 1 °K per mW, 1 mW of heat dumped into the cavity results in a 1°K temperature rise. In the example calculation of Fig. 2.2, 6 mW pump is required to generate 2 mW long-wavelength output. If all of the remaining 4 mW is converted to heat--a pessimistic assumption--the temperature rise of the long-wavelength cavity is only 4°K!! This is in contrast to electrical pumping, in which several tens of °K temperature rise could be expected.

In short, our theoretical predictions show that optically pumped long-wavelength VCSELs should work extremely well, giving us confidence to proceed to the experimental work described in the next section.

III. CW Device Results

CW optical pumping experiments during this program have fallen into two categories. In our first and earliest set of experiments, we used a Titanium:Sapphire (Ti:Sapphire) laser operating at 935 nm to perform CW optical pumping of 1550 nm VCSELs. This experiment allowed us to determine the required pump power, and verify that it is within range of 980 nm VCSEL power levels. Having verified low required pump powers, we demonstrated CW 1550nm operation using an electrically pumped 980 nm VCSEL pump attached to the 1550 nm VCSEL by optically transparent adhesive. These represent our second category of experiments. We start with a summary of Ti:Sapphire experiments.

A. Ti:Sapphire pumping

Two device designs have been investigated with Ti:Sapphire pumping. Figure 3.1 shows the first structure, which uses 4 quantum wells placed on two separate peaks of the optical standing wave in the cavity. Approximately 1 micron of absorber surrounds these quantum wells. The bottom mirror in this structure is a 30 period wafer-fused GaAs/AlAs mirror, and the top mirror is a 9 period SiO_2/TiO_2 dielectric mirror. Index guiding in this structure is accomplished by etching approximately 1.5μm into the long-wavelength cavity, before deposition of the top dielectric mirror.

Figure 3.2 summarizes the results obtained with this structure. The peak power is approximately 0.6 mW. Even more impressive is the fact that this structure uses only 4 *lattice-matched* quantum wells, compared to 7 *strain-compensated* wells in the structure of Fig. 1.1. Because strain-compensated wells offer more gain per well than lattice-matched wells, the total optical gain available in our structure is less than half that in the structure of Fig. 1.1. Despite this, our structure still lases cw at room temperature, with considerable output power. This is because the absence of dopant-induced optical loss and resistive heating combine to dramatically reduce threshold gain.

Despite the success of Figs. 3.1 and 3.2, analysis of the data reveals a residual optical loss of around 1%. The most likely cause of this is the deep (1.5 μm) etch inside the cavity, shown in Fig. 3.1. In our next generation of devices, we etched only about 0.15 μm inside the cavity, and employed two fused mirrors, as shown in Fig. 3.3. Recent work using selective oxidation of AlAs in 980 nm VCSELs has shown that low-loss index guiding occurs if the vertical extent of the index discontinuity is on the order of 0.1 μm. Also in Fig. 3.3, we reduced our number of quantum wells to two, which is unprecedented in long-wavelength VCSEL work. We do introduce compressive strain however, to increase the gain per well.

Using the structure of Fig. 3.3, we obtained the results of Fig. 3.4. Maximum output power is now 2.3 mW, which is beyond the telecommunication benchmark of 1 mW. Although the pump power of 13 mW required to obtain this means that the 2.3 mW would be obtained from a broad area device, we expect that devices with sizes matching single-mode fiber could deliver 0.5 mW of power, using a 980 nm VCSEL pump.

Our results in Fig. 3.4 are still not quite as good as predicted by theory in Section II. One reason for this appears to be an excess residual loss of 0.3%, instead of the 0.1% loss assumed in the calculation. Also, the quantum wells do not appear to be perfectly aligned with the optical standing wave in our device, which increases threshold. Both of these factors can be improved upon, but our experiments already demonstrate that VCSEL power

levels are adequate for 1550 nm operation. We therefore move to a discussion of 980 nm VCSEL pumping 1550 nm VCSEL experiments.

B. 980 nm VCSEL pumping

Figure 3.5 summarizes our VCSEL pumping VCSEL experiments. As shown, we have pumped a double-fused 1550 nm VCSEL structure using both a top-emission ion-implanted 980 nm device and a bottom emission oxidized 980 nm device. The ion implanted device exhibited high threshold, so the 1550 nm VCSEL it pumped also exhibited high threshold. Despite this, 0.25 mW room temperature power was obtained, all of which was in a single transverse mode.

The oxidized bottom emitter was a much better pump laser, so the 1550 nm current threshold was reduced to 5 mA, and output power increased to 0.5 mW room temperature. This power was not entirely single-mode, but we feel that simple design modifications could make it so.

The results of Fig. 3.5 demonstrate conclusively the success of the VCSEL pumping VCSEL approach, and also that the Ti:Sapphire experiments are a good predictor of 980 nm pumping performance.

IV. WDM Array results

Lastly in this program, we have demonstrated CW operation of WDM arrays, pumped by a Ti:Sapphire laser at VCSEL power levels. Fig. 4.1 shows the unintentional wavelength variation across a sample containing devices of the type pictured in Fig. 3.1. This variation arose from growth non-uniformity, but demonstrates CW lasing over a 40 nm span. This indicates that wide-span WDM arrays are feasible.

Figure 4.3 shows an intentionally designed WDM array, fabricated using a technique described with the aid of Fig. 4.2. As Fig. 4.2 shows, we selectively etch away layers of an intracavity superlattice prior to wafer fusion of the second mirror. This adjusts the wavelength from device to device. A rather surprising result of this investigation is that it is possible to wafer fuse to a stepped surface. Originally we considered this impossible, and thought a dielectric mirror would be necessary for the second mirror. In reality, we can still exploit the superior thermal properties of a wafer fused mirror by fusing a second mirror. Although the physics of the fusing process with stepped surfaces are not well understood, we have made WDM arrays with the characteristics of Fig. 4.3.

Fig. 4.3 shows an optically pumped 4-channel array, with average channel spacing of 2 nm. Again, the slight variation in channel spacing is not yet well-understood, but may be related to the imperfect selectivity of the wet chemical etch. Further work is required to quantify this.

V. Summary

In this program, we have developed a technology for WDM 1550 nm VCSEL arrays, using 980 nm VCSEL pump lasers to optically pump 1550 nm VCSELs. This essential device design has demonstrated 2.3 mW output power in Ti:Sapphire experiments, and 0.5 mW 1550 nm output power by electrical pumping of a 980 nm VCSEL. We have also demonstrated 0.25 mW 1550 nm output power in a single transverse and longitudinal mode, by electrical pumping of a 980 nm top emission VCSEL.

By intracavity superlattice chemical etching and double fusion, we have demonstrated a nominally 2 nm spacing 4-channel WDM array pumped by a Ti:Sapphire laser at VCSEL power levels. The next logical step is to integrate such an array with an array of 980 nm pump VCSELs. This scheme of using 980 nm pump VCSELs to generate a low threshold 1550 nm WDM laser array is the primary technical contribution of this program.

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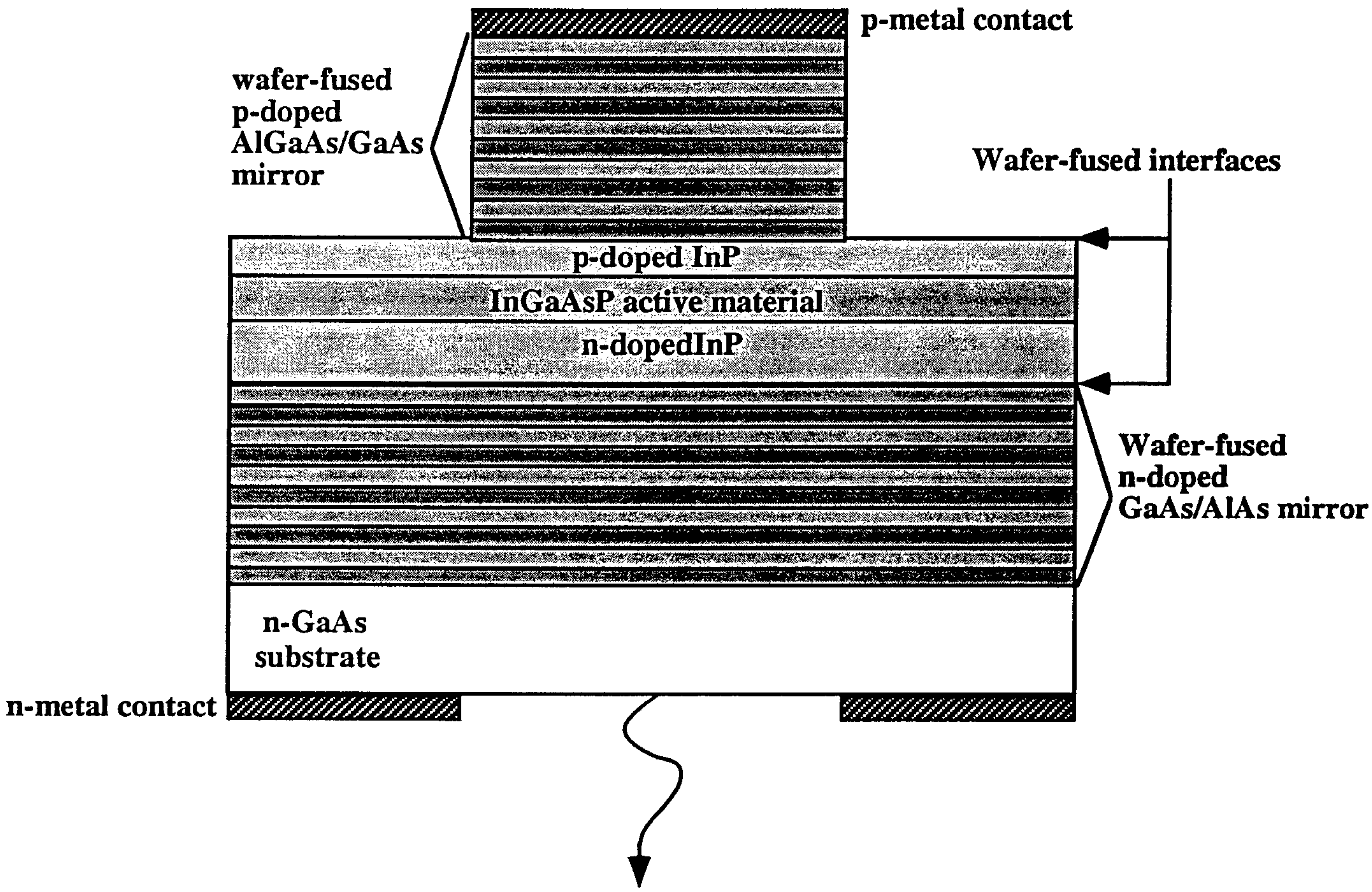
4. A.L. Holmes, et al, "Strained InGaAsP Single-Quantum-Well lasers Grown with Tertiarybutylarsine and Tertiarybutylphosphine," *Applied Physics Letters* Dec. 20, 1993, vol. 63, n0.25, pp. 3417-3419.



- **7 Strain-compensated quantum wells**
- **CW operation with 30 μwatts output power**

Figure 1.1: Double-fused 1550 nm VCSEL by Babic, et al at UCSB.

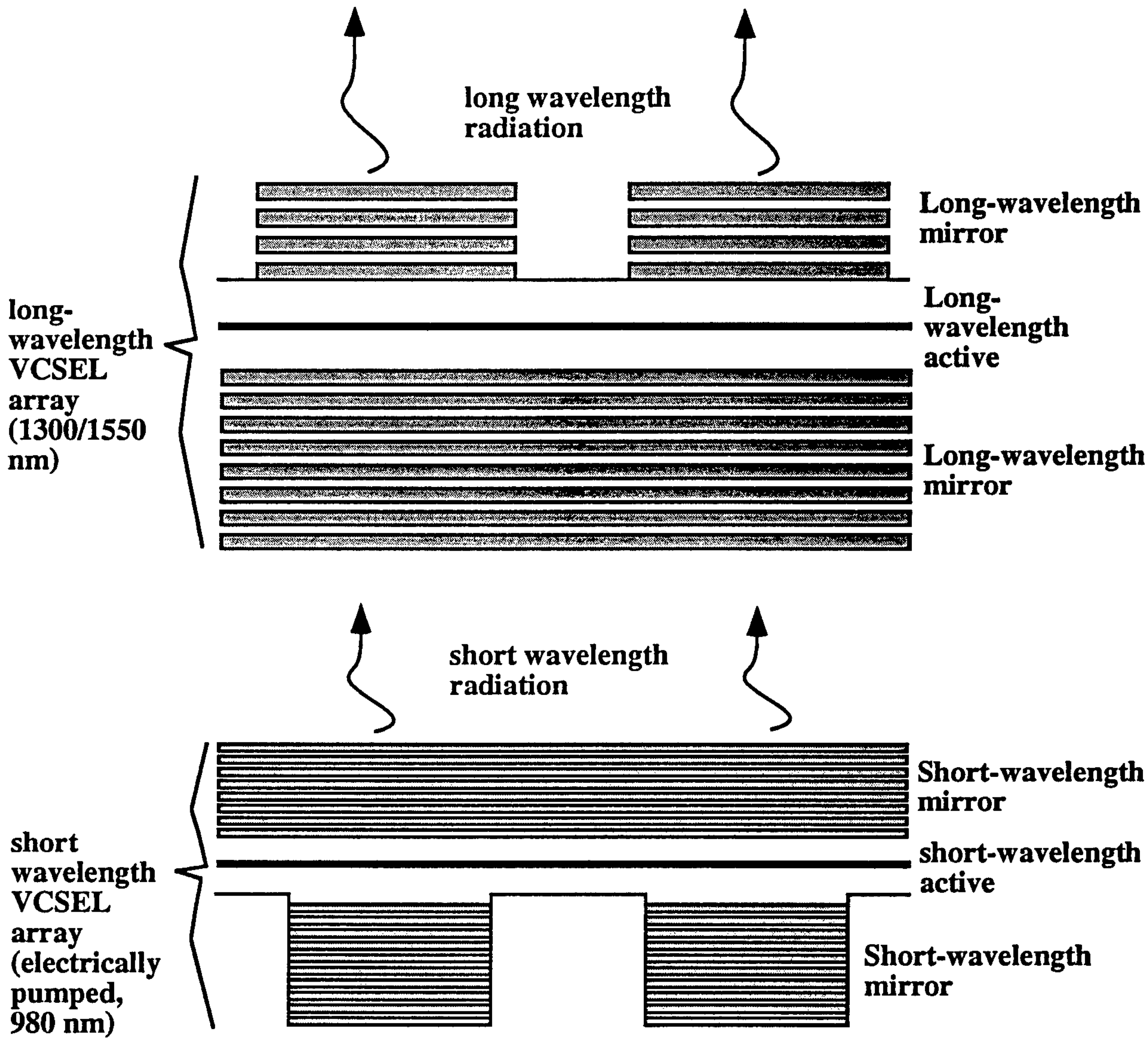


Figure 2.1: Long-wavelength VCSEL array with vertically integrated short-wavelength VCSEL pump.

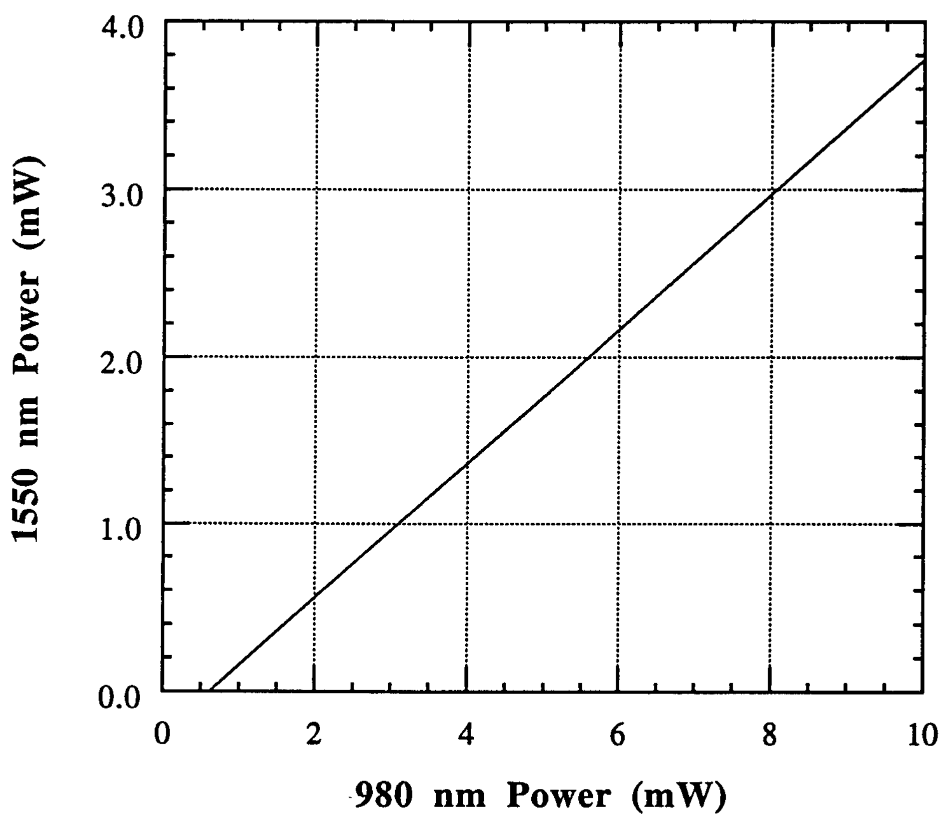


Figure 2.2: Theoretical power conversion if η_i=0.85, T/(T+A)=0.75

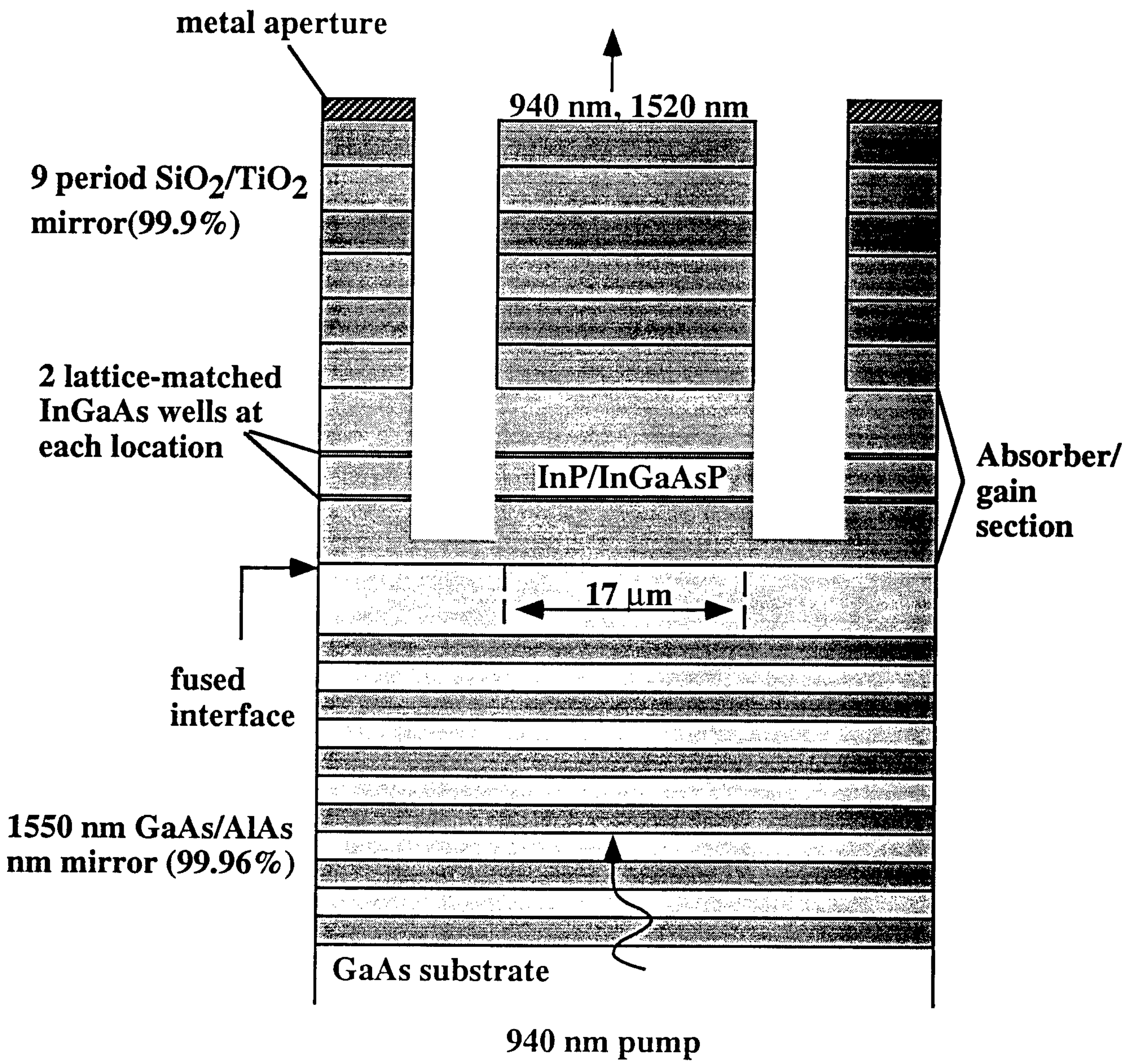


Figure 3.1: 1st experimental structure for long-wavelength VCSEL.

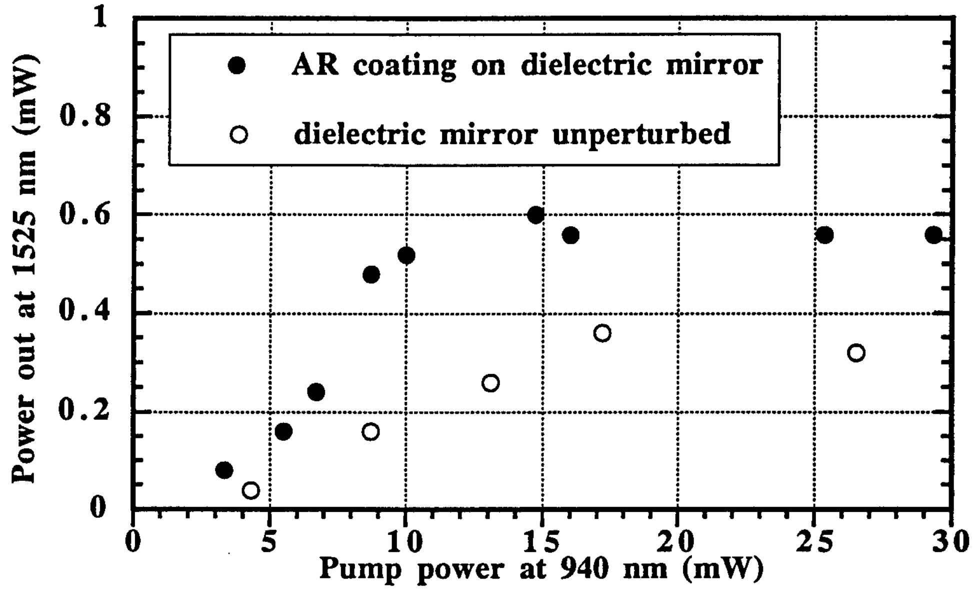


Figure 3.2: Power conversion for two different top mirror reflectivities. The AR coating doubles the output mirror transmission.

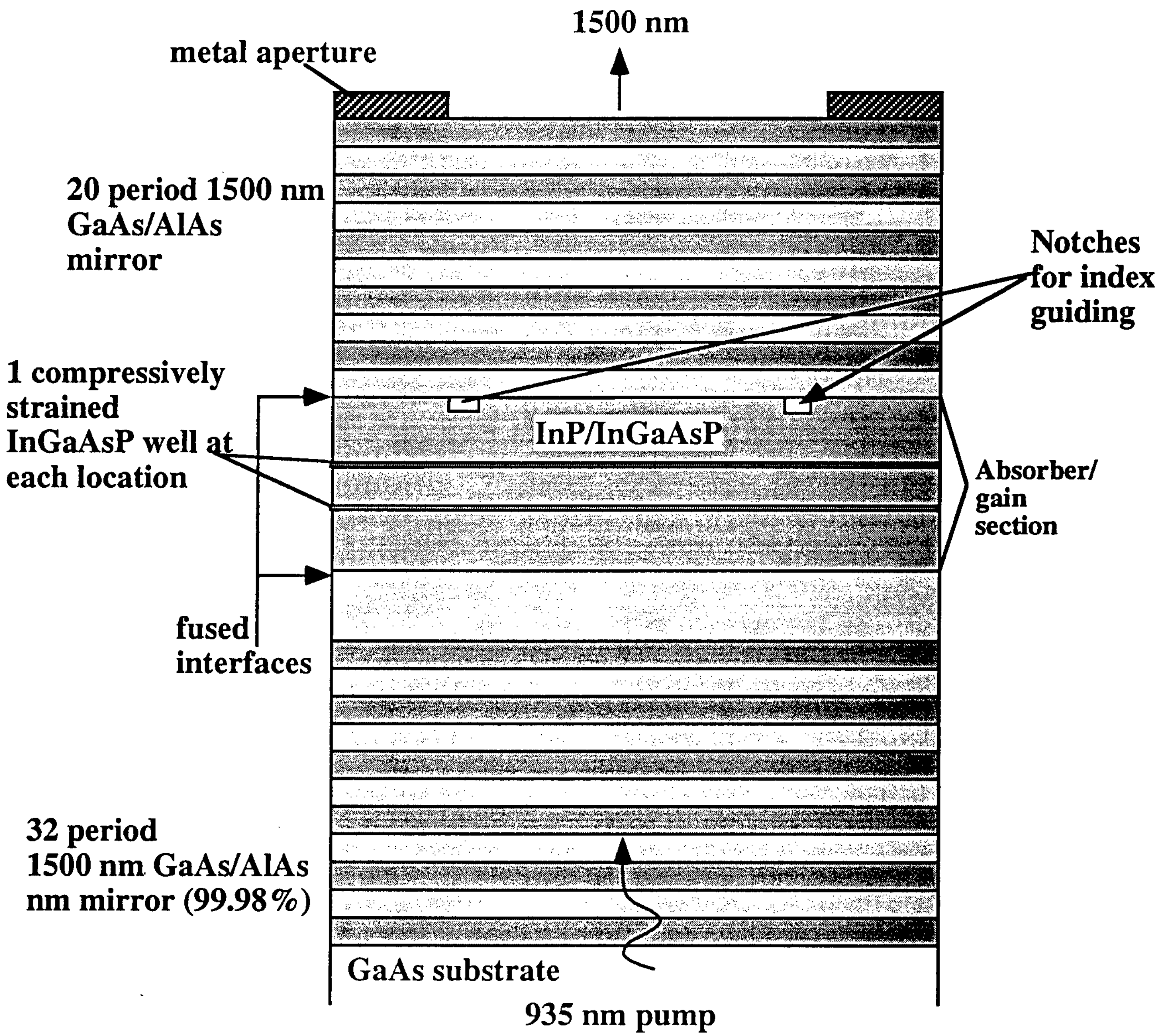
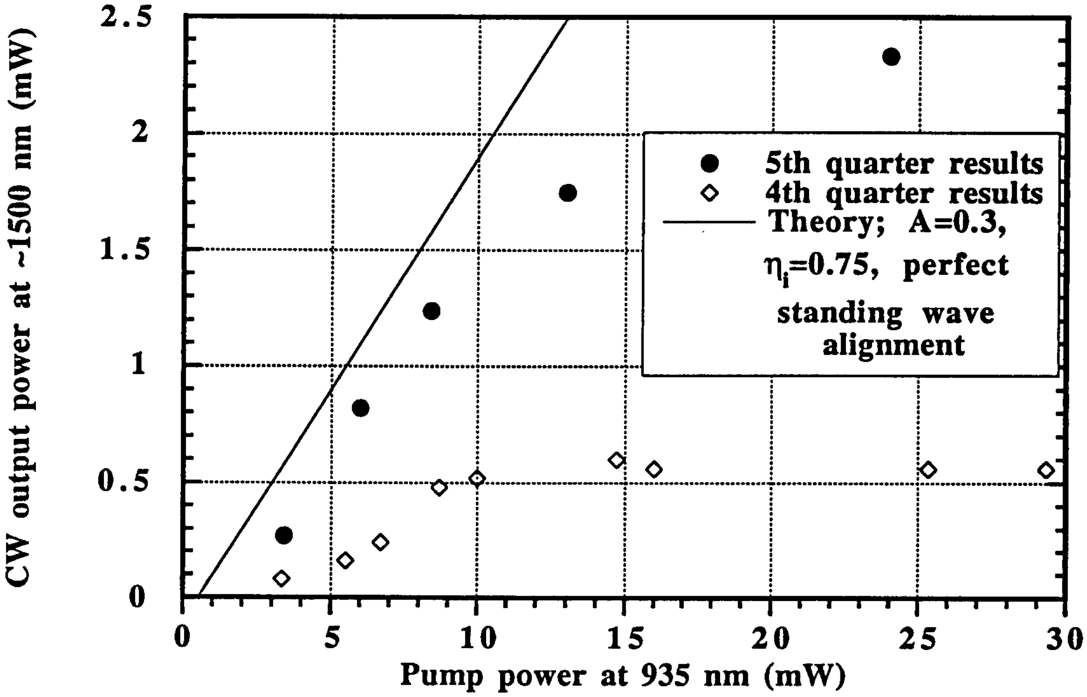


Figure 3.3: Double-fused, optically pumped VCSEL structure.



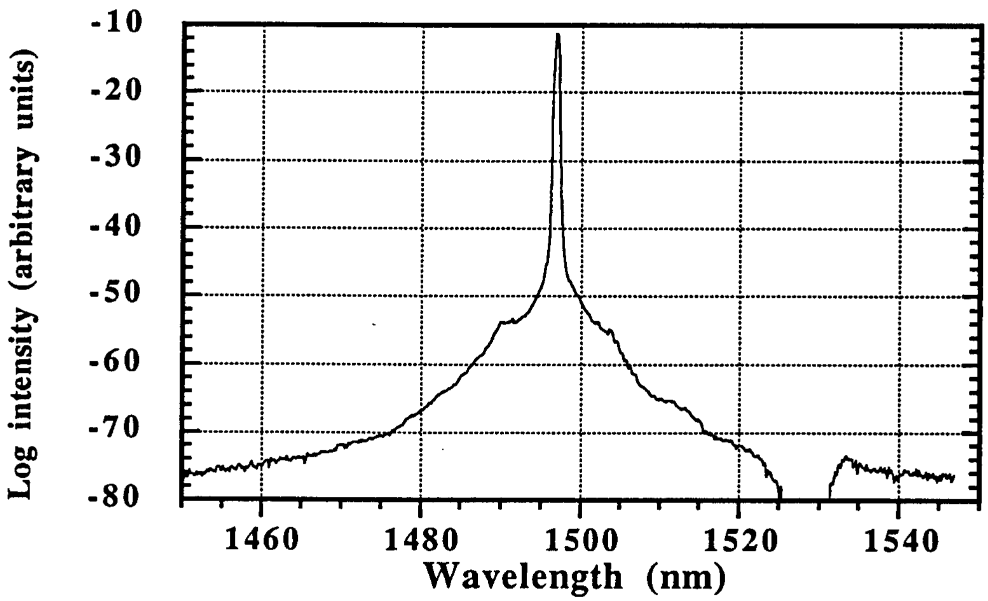


Figure 3.4: Optically pumped long-wavelength VCSEL results. High power obtained by double-fused structure. Lower power represents Fig.3.2 results.

16 μm diameter Long-wavelength VCSELs with 2 quantum-well active regions, pumped by top and bottom-emitters

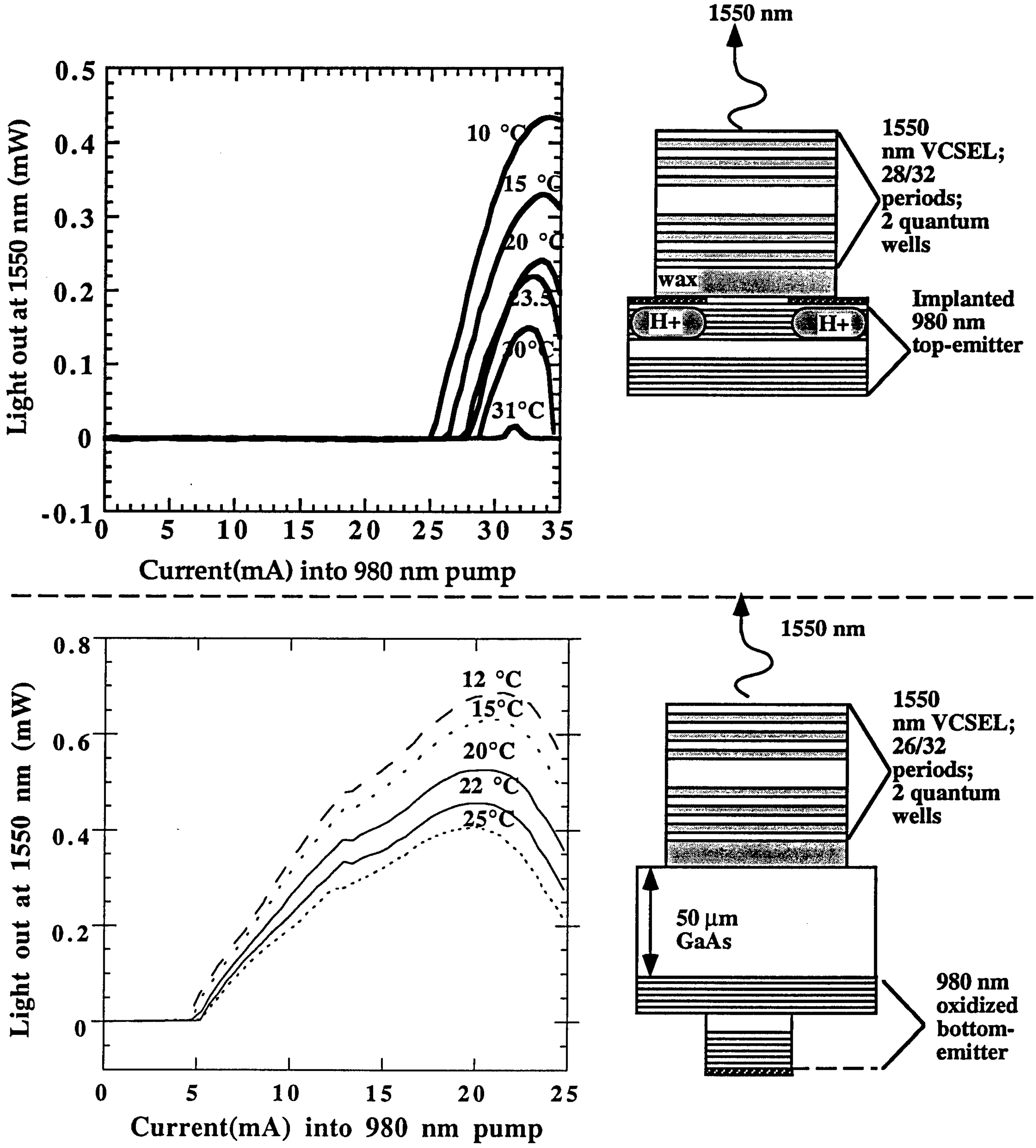


Figure 3.5: Performance of 1550 nm laser with two different 980 nm pump lasers.

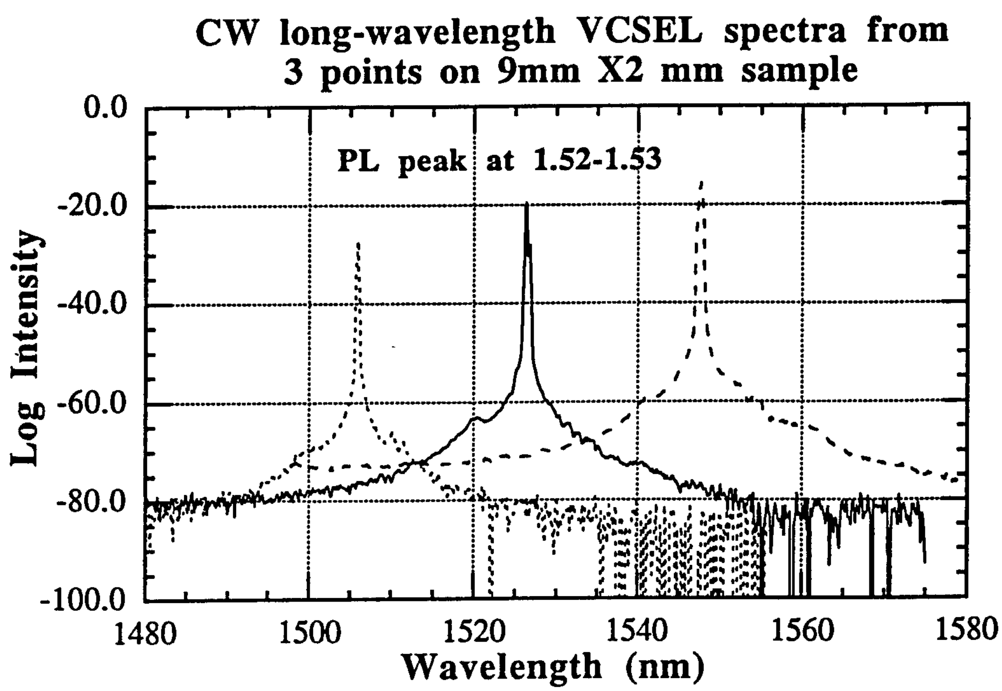


Figure 4.1: CW spectra over a 40 nm range.

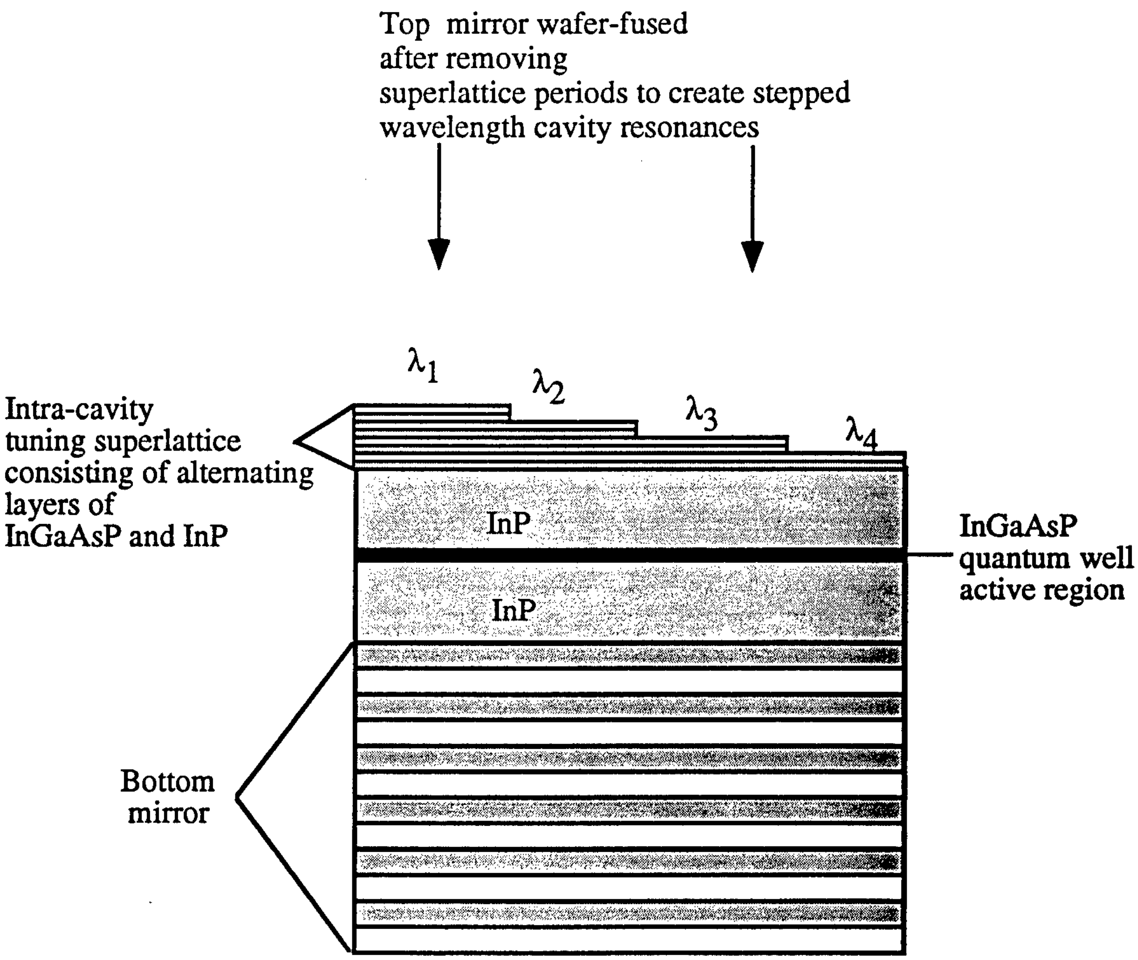


Figure 4.2: WDM array by selective etching of intracavity superlattice

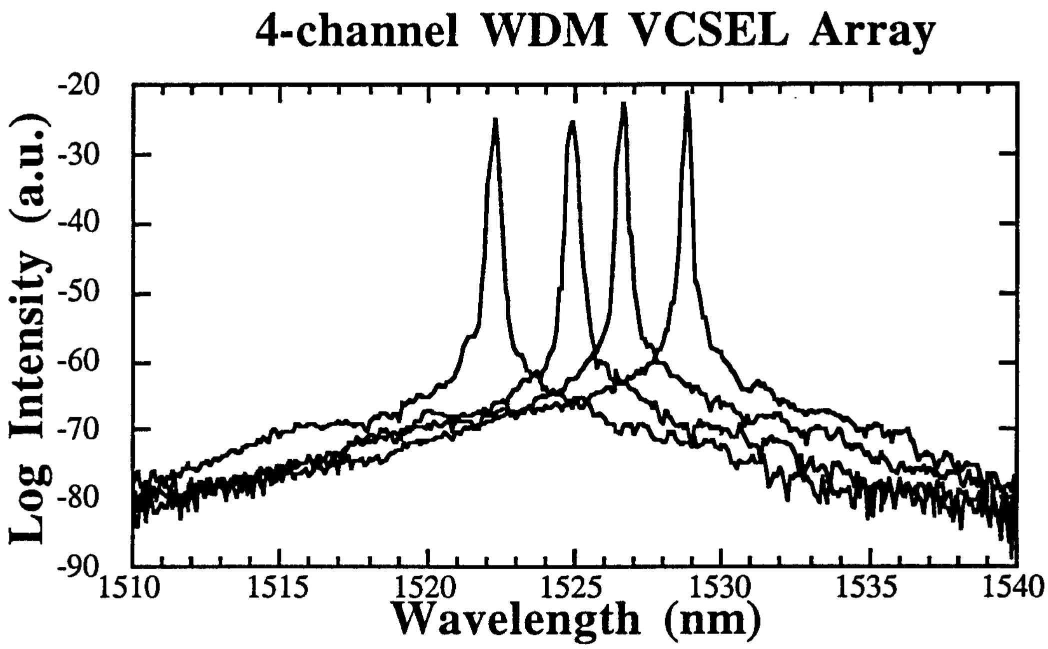


Figure 4.3: 4-channel WDM array spectra